NSCL Power Supply Maintenance and FRIB Power Supply Status Update

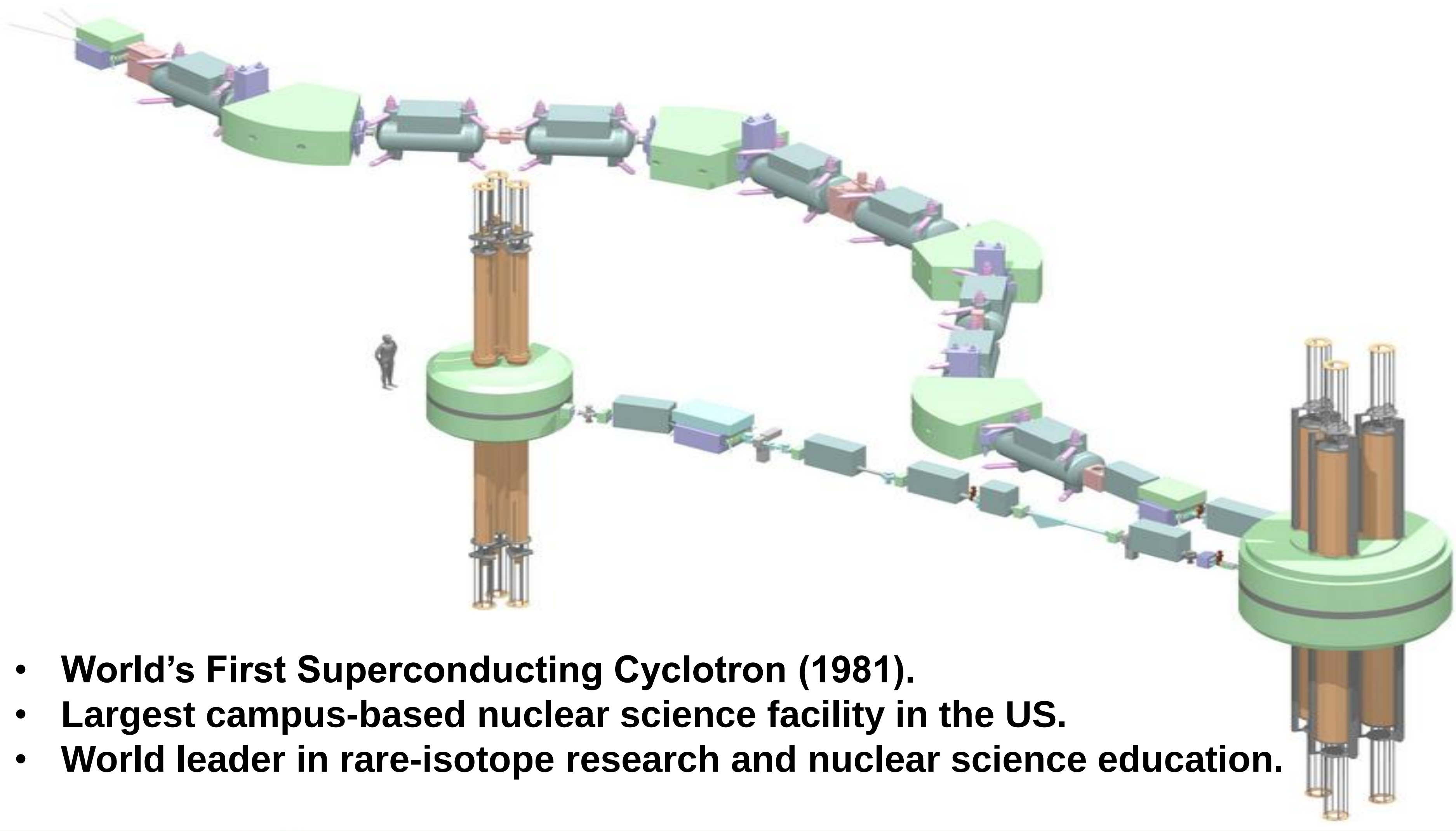
Brian K. Vaughn
Power Supply Engineer

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

NSCL – National Superconducting Cyclotron Laboratory



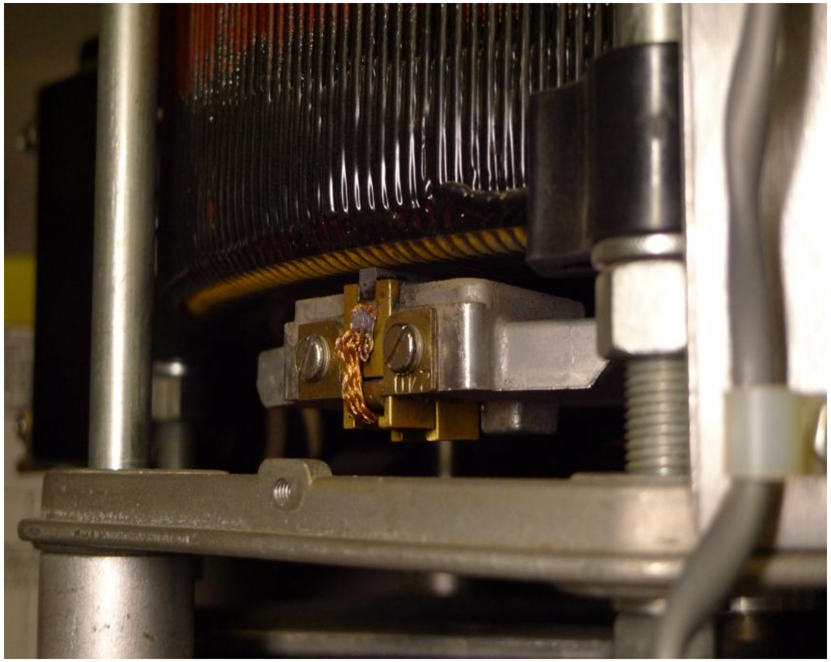
- World's First Superconducting Cyclotron (1981).
- Largest campus-based nuclear science facility in the US.
- World leader in rare-isotope research and nuclear science education.

NSCL Power Supplies

- 989 Power Supplies support NSCL operations.
  - 521 High Voltage power supplies (HV PS).
  - 242 Superconducting Magnet power supplies (SCM PS).
  - 226 Room Temperature Magnet power supplies (RTM PS).
- 88 different model numbers.
- 160 spare power supplies.
- 133 SCM PS in operation were designed and built in-house.
- 762 NSCL power supplies will remain in operation after transition to FRIB accelerator line.
- 99% overall availability – most failures due to high ambient temperatures.
  - Tracked in facility operating log.

Power Supply Preventative Maintenance at NSCL

- All PS installations tested at rated voltage and current.
- Hipot testing of all HV components and HV floating structures to prevent installation of defective components or assemblies.
- Networked floor moisture sensors to alert for leaking coolant water.
- Other maintenance tasks include:
  - Periodic inspection of critical components – transistor fuses, cooling fans, etc.
  - Test of water flow switches.
  - Replacement of aged electrolytic capacitors.



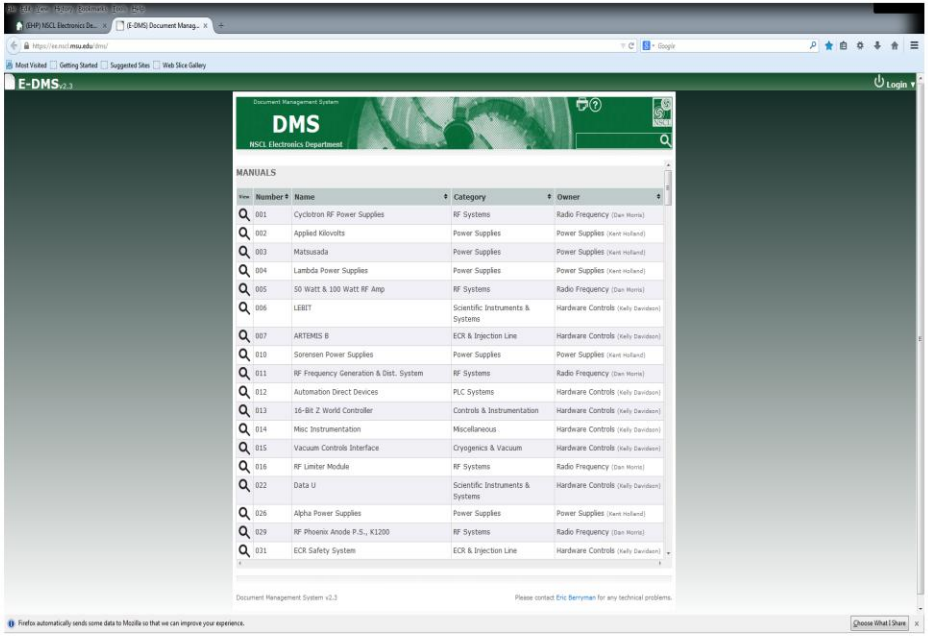
Main Magnet Power Supply Variacs require periodic cleaning & brush replacement.

Reliability Upgrades at NSCL

- Coupled-Cyclotron accelerator must operate until FRIB linear accelerator is operational sometime between 2018 and 2020.
- All other experimental equipment will continue in service after FRIB line commissioning.
- This complicates upgrade priorities – power supplies for the coupled cyclotrons must have high (>>90%) availability, but will be out of service in 4-6 years.
- Requires extensive planning and analysis based on:
  - Reliability history for specific equipment
  - Age of equipment
  - Availability of spares
  - Time-to-repair or replace
  - Cost & funding

Power Supply & Equipment Tracking at NSCL

- Document Management System (DMS) used as database for all Electrical Engineering documents.
- Periodic power supply inventories are undertaken to track equipment status and location.



NSCL Lab-Wide Spare Power Supply Inventory

PS Model / Area	K1200 Balcony	Upper K1200 Balcony	K500 Balcony	Roof	West High Bay	ECR Control Room	K500 TCPS Area	A1900 PS Area	North Hall	N2 Vault	D-Line PS Area	ReA3 High Bay	ReA12 High Bay	East High Bay Extension	East High Bay	East High Bay - ReA3 Area	S800 Vault	South Hall	Electronics Shop	PS Group Offices & Labs	Total Number
ACCOPIAN																					
150PT2AFHMP																			1		1
Y022LX2000																				1	1
ALPHA POWER SUPPLIES																					
120V/500A ALPHA																					0
10V/200A ALPHA																					0
160/1000				1																	1
APPLIED KILOVOLTS HP010Z1P025																				1	1

Power supply database and planned PS tracking & documentation improvements

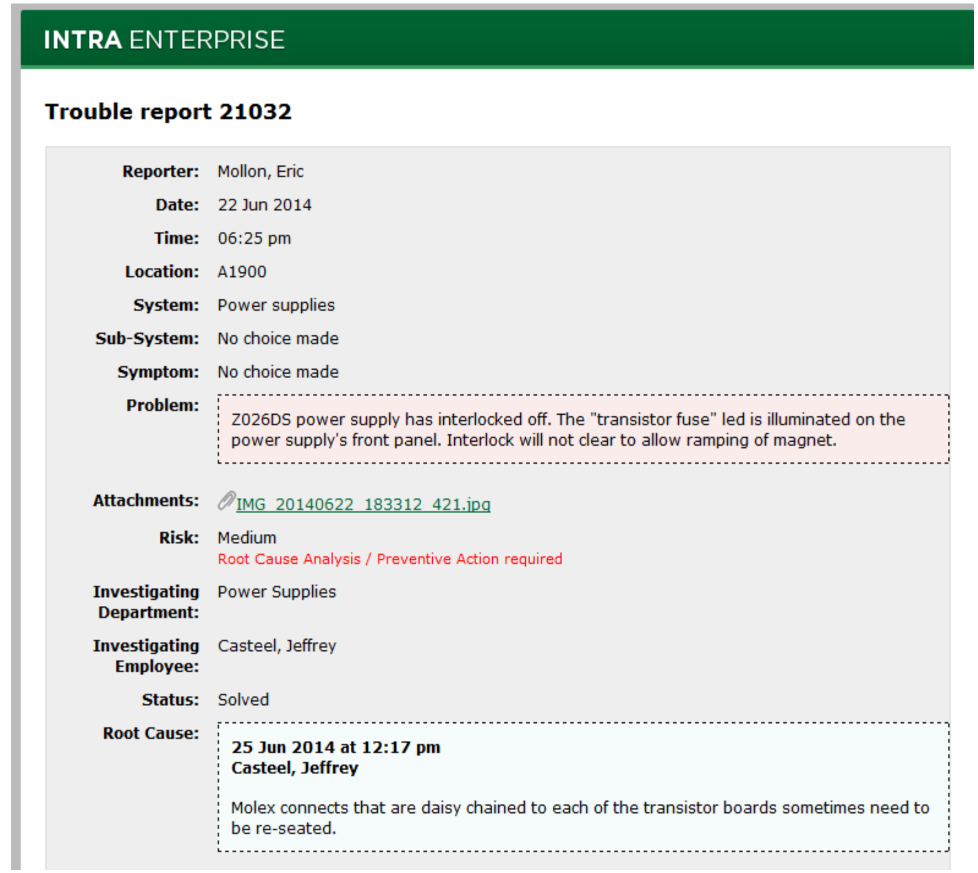
- Each PS in service is tracked:
  - Location (by area) and application.
  - PS address and name.
  - DIP switch setting and calibration.
  - Input power requirements and output current & voltage.
  - Communication protocol (serial, Ethernet, or analog).
- Planned enhancements to PS tracking:
  - Breaker panel, circuit breaker number, and location corresponding to each PS.
  - Rack location of each PS.
  - Magnet application and information by PS.
    - » Magnet inductance, mutual inductance.
  - Migration of DMS database to ADEPT.
  - Implementation of FRIB Controls relational database.
- Further details next slide – to develop solution for PS history tracking.

PS Systems Database

- Configuration
  - Current facility configuration
    - slots, device type, device properties
- Logbook
  - Maintenance / troubleshooting task details
- Magnets
  - Magnet name, location
- Cables
  - Cable information
    - Signal, type, tags, source, destination
  - Cable steps / status
    - Pull, field test, label, bench terminate, bench test, field terminate
- Calibration
  - Calibration constants, frequency compensation constants
  - Reminders
  - Device information
    - Serial number, model, calibration cycle, location, custodian, standard
  - Device model information
    - Model, manufacturer, calibration cycle, manual
- Maintenance
  - Periodic maintenance tasks, reminders, status
- Naming
  - PS name, cable name, magnet name
- Control Signals (PV)
  - PS signal names
- The controls database tracks the current facility configuration and give reminders for maintenance / calibration tasks, however it does not keep details of device history
- A PS systems database will be developed to keep history of:
  - System configuration and spares
  - Detailed history of each PS
    - Failures, RMAs, firmware
  - Metadata
    - Serial number, calibration data, firmware/software version

Power Supply Trouble Reports at NSCL

- Trouble Report system available to all lab employees.
- Used to initiate and track action on reports of safety concerns and engineering issues.
- Power supply group at NSCL has investigated & resolved 300+ trouble reports since system rollout (2006).


INTRA ENTERPRISE

Trouble report 21032

Reporter:	Mollon, Eric
Date:	22 Jun 2014
Time:	06:25 pm
Location:	A1900
System:	Power supplies
Sub-System:	No choice made
Symptom:	No choice made
Problem:	Z026DS power supply has interlocked off. The "transistor fuse" led is illuminated on the power supply's front panel. Interlock will not clear to allow ramping of magnet.
Attachments:	IMG_20140622_183312_421.jpg
Risk:	Medium Root Cause Analysis / Preventive Action required
Investigating Department:	Power Supplies
Investigating Employee:	Casteel, Jeffrey
Status:	Solved
Root Cause:	**25 Jun 2014 at 12:17 pm** **Casteel, Jeffrey** Molex connects that are daisy chained to each of the transistor boards sometimes need to be re-seated.

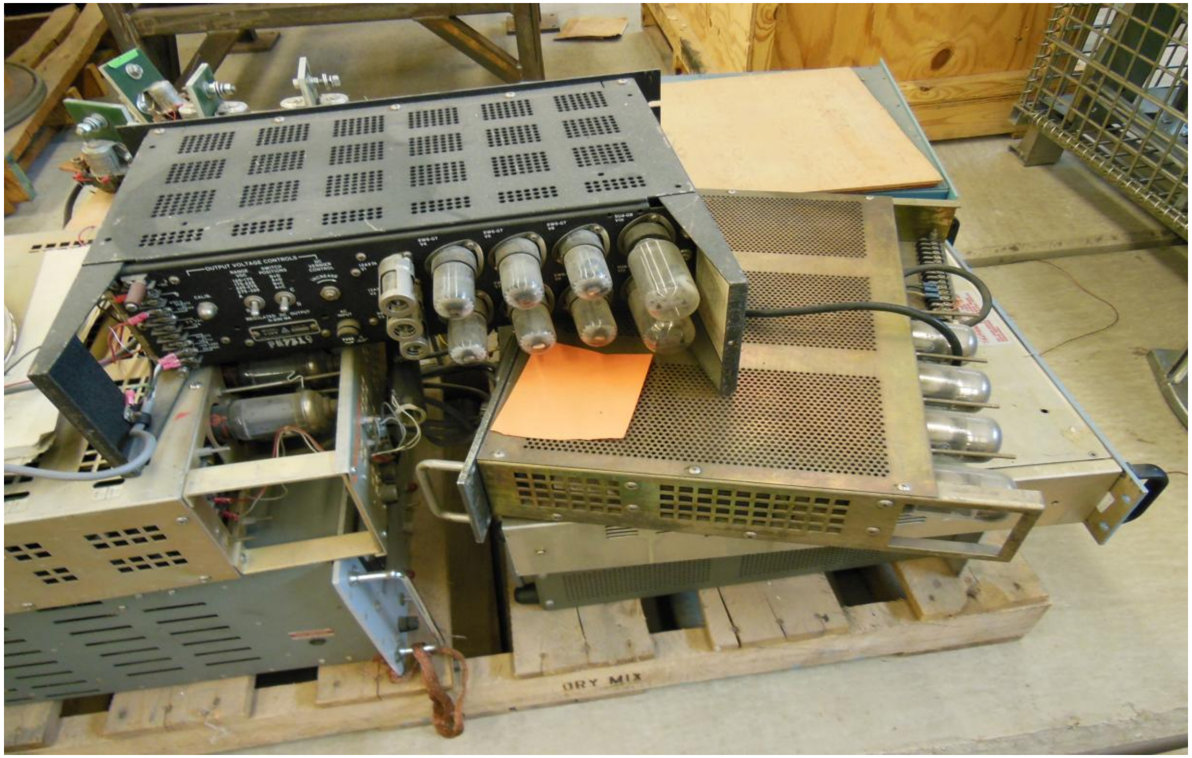
Hazard Mitigation at NSCL

- Electrical safety training required for all lab personnel.
- Job safety analysis required for all non-standard equipment procedures.
- Personal Protection Equipment & clothing issued to all maintenance personnel.
- Licensed electricians perform power distribution tasks.

Lockout/Tagout mandatory for servicing electrical equipment and quarantine.

New Power Supply Initiatives at NSCL

- Replacement of linear power supplies with switch-mode converters.
- Implementing improved PS labeling requirements and on-site documentation.
- Implementing more consistent terminal cover requirements – anything with ≥ 50V, or ≥ 10J stored energy, or ≥ 10W power capability.



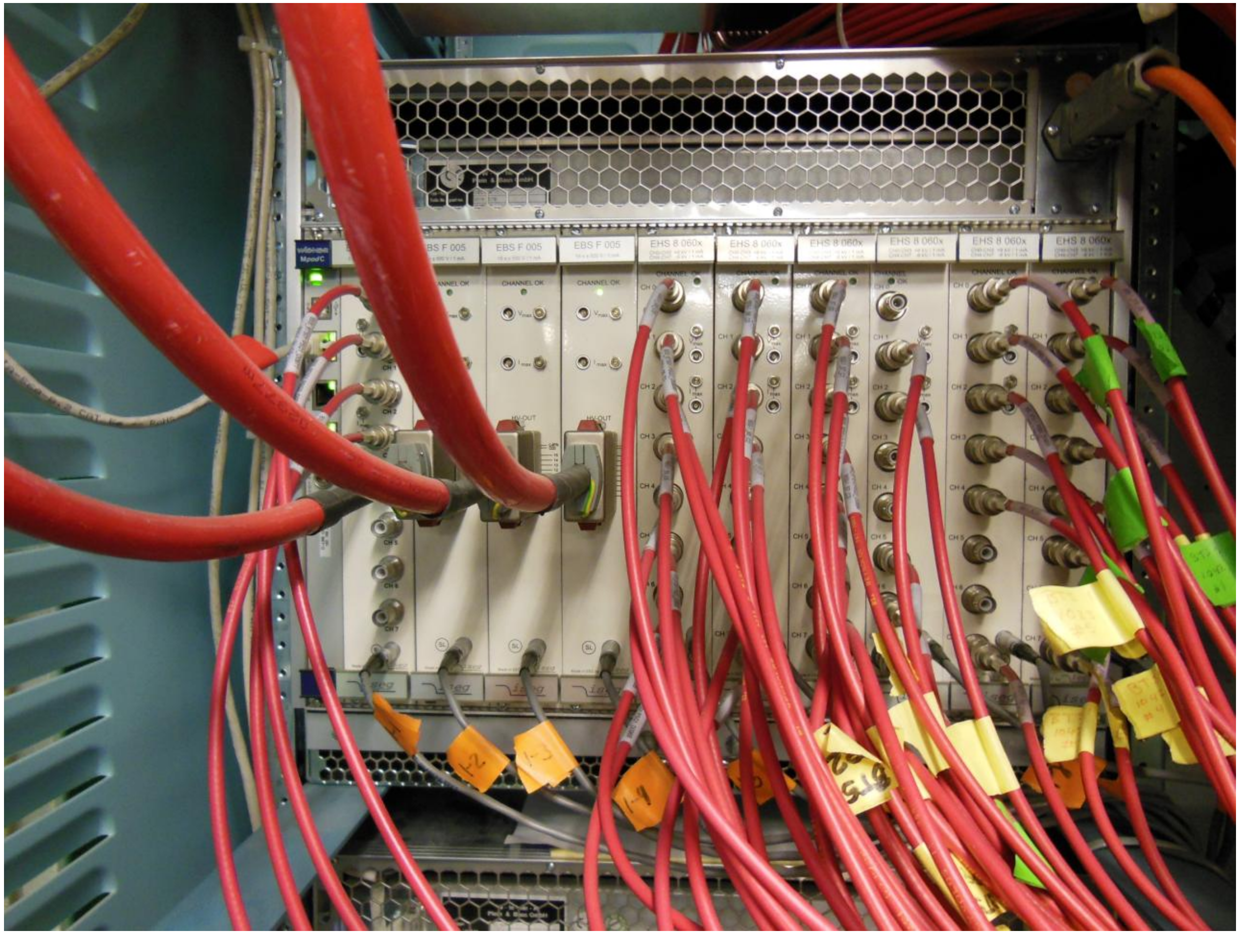
- Replacement of obsolete power supplies.

FRIB – Facility for Rare Isotope Beams

- $730M project, funded by DOE and MSU, to replace coupled-cyclotron accelerator with a “folded” linear accelerator.
- Upgrades facility to most powerful rare ion beam in world – 400kW.
- Requires purchase, test, and installation of 847 new power supplies.

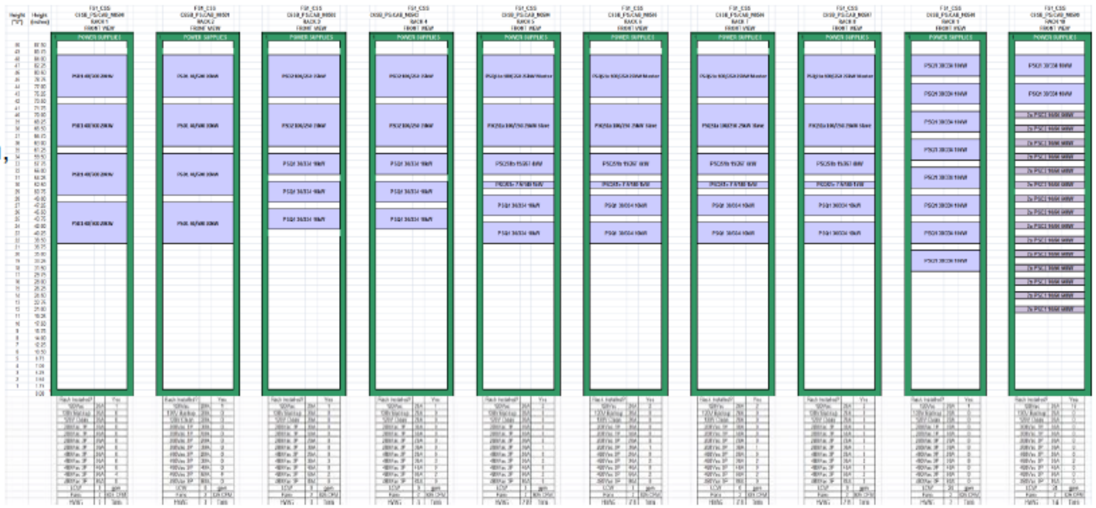
Power Supplies for FRIB

- Planning and specification largely complete – acquisition underway.
  - 299 RTM PS's.
  - 191 CM Heater PS's.
  - 287 SCM PS's.
  - 70 HV PS's. →
- 1609 total power supplies will support FRIB.
- Two new hires in Power Supplies Group.
- Emphasis on reliability, conversion efficiency, and power factor correction.
- Hipot testing up to 120 kV required for Ion Source Platform.



System Requirements and Integration Requirements are Defined and Tracked

- Power supply integration
  - Conventional Facilities
    - » Rack / Utility layouts →
    - » Alternating Current (AC) power, Heating, Ventilation, and Air Conditioning (HVAC), cooling water
    - » DC leads
    - » Cable tray
    - » Conduit
  - Controls
  - Accelerator / Magnet Systems
    - » Power supply requirements / ICD



- Completed documents
  - Parameter List (T10501-BL-000002)
  - FRIB Power Supply Requirements ASD(T30102-SP-000290), ESD(T40303-SP-000288)
  - Preliminary FRIB Rack Counts and Power Estimate (T10503-CM-000037)
  - PS Systems Integration ICD (T31209-CM-000111)
  - PS Technical Description and Specifications SRD (T31209-SP-000084)
  - SCM PS Acquisition Strategy (T31209-TD-000472)
  - PS Production Plan (T31209-PL-000108)
  - Preliminary SCM PS Specs (T31209-SP-000152)
  - Preliminary RT Specifications (T31209-SP-000153)
  - HV PS Specifications (T31209-SP-000154)
  - Production Superconducting Magnet Power Supply ACL Plan (T31209-VP-000114)
  - First Article and Pre-Production Superconducting Magnet Power Supply ACL Plan (T31209-VP-000092)
  - Production High Voltage Power Supply ACL Plan (T31209-VP-000113)
  - First Article High Voltage Power Supply ACL Plan (T31209-VP-000069)
  - Room Temperature Magnet Power Supply ACL Plan (T31209-VP-000095)
  - Space Use Case for Power Supplies (T31209-TD-000257)
  - Specification for Ion Source High Voltage DC Isolation Transformer (T30504-SP-000188)

Power Supply Interfaces Defined and Tracked

- This FRIB interface tracker spreadsheet serves as a tool to track Interface Requirements Documents between systems
- Interface tracker shown →

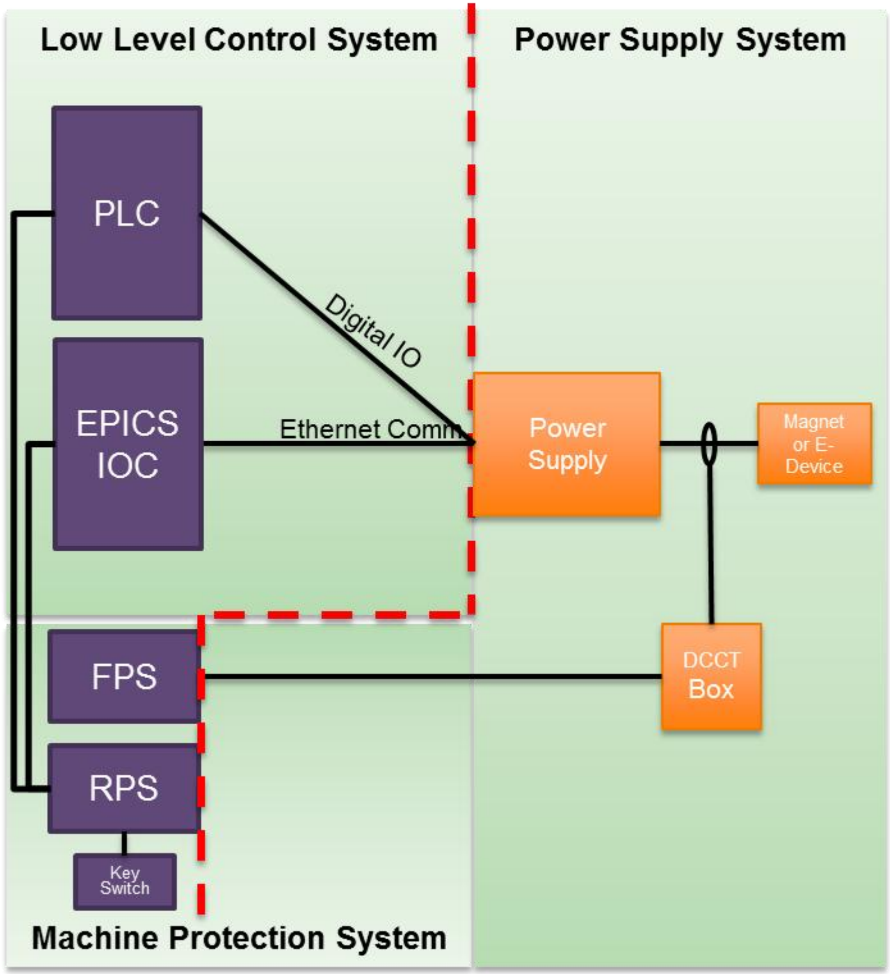
Legend	
O	ICD not required
Y	ICD required, not yet in DCC
T	Link to ICD(s), but details T.B.D. in ICD
V	Link to ICD(s)

Acronyms	
ASD	Accelerator Systems Division
CFD	Conventional Facilities Division
ESD	Experimental Systems Division

Avg.% 49			T.3.02 Cryogenic Systems	T.4.02.01 Target Area Utilities	T.4.02.02 Target Area Remote Handling	T.4.02.03 Target Area Non-Conv. Utilities	T.4.03.01 Frag. Sep. Beam Physics	T.4.03.02 Diagnostics	T.4.03.03 Preseparator Magnets	T.4.03.04 Preseparator Mechanical Systems	T.4.03.05 A 1900 Reconfiguration	T.4.03.06 Power Supplies
%avail.												
63	Cryogenic Systems	T.3.02	O									
29	Target Area Utilities	T.4.02.01	O	O								
33	Target Area Remote Handling	T.4.02.02	O	O	O							
11	Target Area Non-Conv. Utilities	T.4.02.03	Y	Y	Y	O						
100	Frag. Sep. Beam Physics	T.4.03.01	O	O	O	O	O					
18	Diagnostics	T.4.03.02	O	Y	Y	O	V	O				
64	Preseparator Magnets	T.4.03.03	V	Y	V	Y	V	O	O			
27	Preseparator Mechanical Syst.	T.4.03.04	Y	Y	Y	Y	O	Y	Y	O		
63	A1900 Reconfiguration	T.4.03.05	V	O	O	O	O	Y	O	O	O	
100	Power Supplies	T.4.03.06	V	V	O	O	O	O	V	V	V	O
89	Vacuum Systems	T.4.03.07	O	V	V	O	O	O	V	V	V	O
46	Low Level Controls	T.4.03.08	Y	O	O	Y	O	Y	V	Y	V	V
0	Target and Material Physics	T.4.03.09	O	O	O	O	O	O	O	Y	O	O
100	Machine Protection System	T.4.06	O	O	O	V	O	V	O	V	O	V
25	Global Timing System	T.3.04.02	O	O	O	O	O	Y	O	O	O	O
20	Central Control Systems	T.3.13.01	O	O	O	Y	O	Y	Y	O	O	V
43	Alignment Systems	T.3.13.03	O	O	Y	O	O	Y	V	Y	V	O
40	Personnel Protection Systems	T.3.13.04	V	O	Y	O	O	O	O	Y	O	V
	ASD Beam Delivery System	T.3.11	O	O	Y	O	O	O	O	V	O	O
	CFD	T.2	V	Y	V	Y	O	Y	O	Y	Y	V
	NSCL	NA	O	O	O	O	O	O	O	O	Y	O

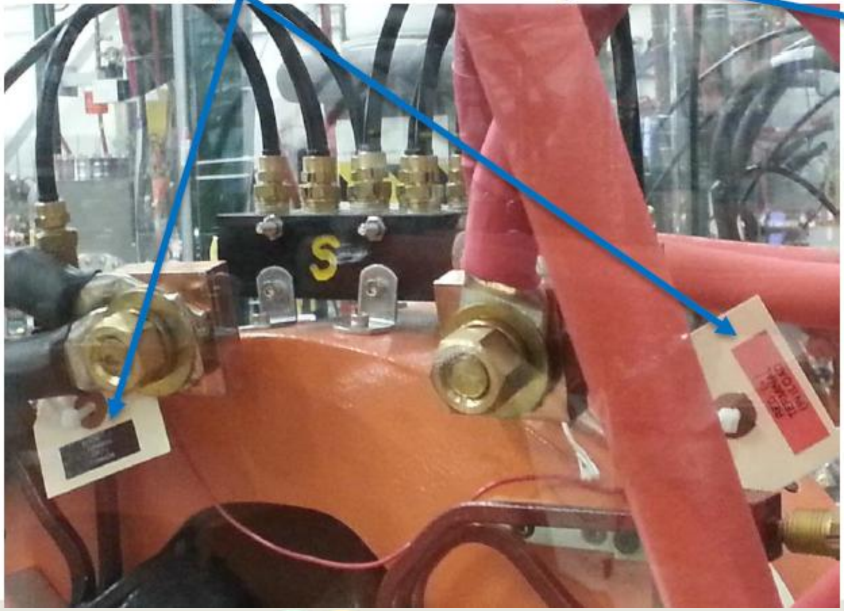
Low Level Control Interface Points Defined

- Controls Group responsibilities
  - Cabling between the control system and power supplies and ancillary equipment
  - Ethernet connection to power supplies
  - Where required FPS ADC
- Power Supply Group responsibilities
  - Selection of power supplies and ancillary equipment
  - Cabling between power supplies and ancillary equipment
  - Installation of Direct Current (DC) leads and power supplies
  - FPS DCCT
    - » and filter if necessary

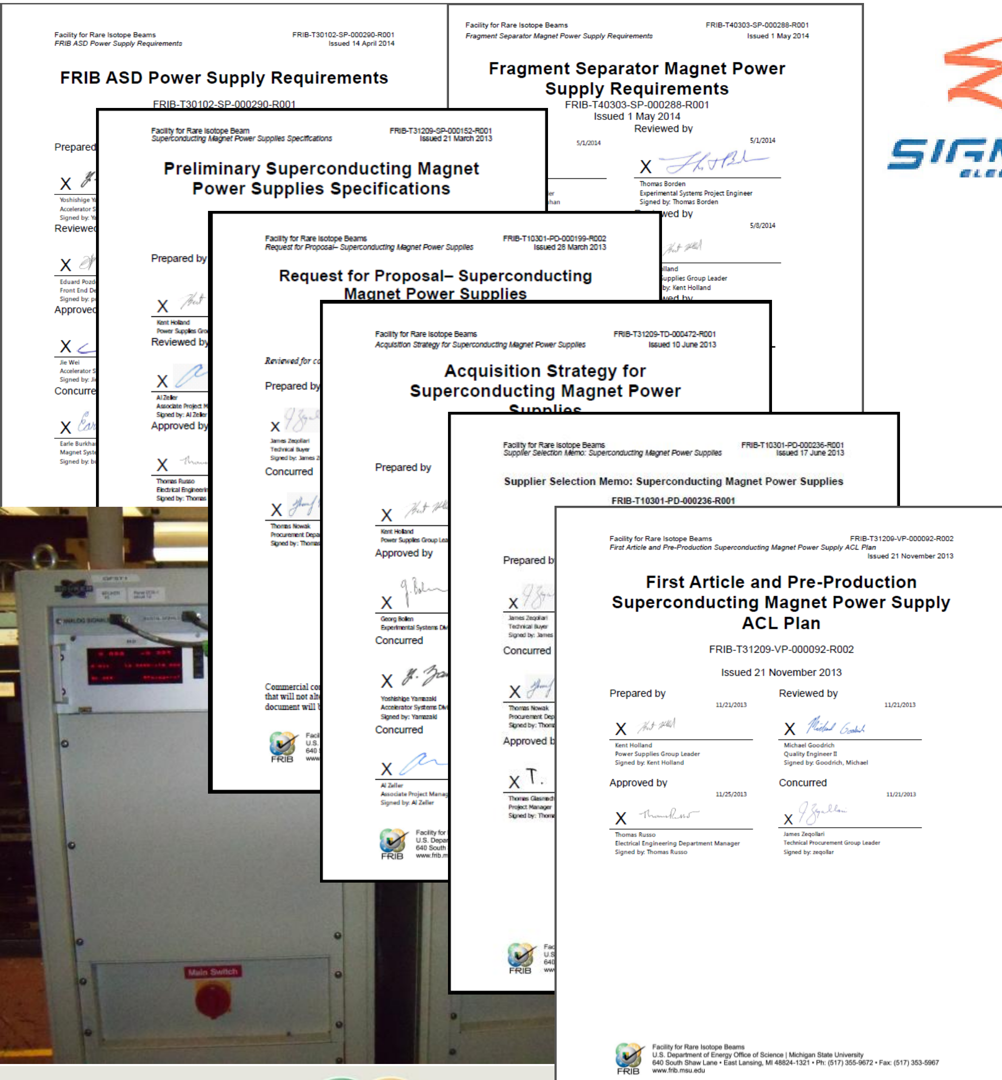


Magnet Interface Defined

- The magnets will be protected by multiple interlocks provided by controls
- The magnet group will provide
  - Terminal block to which the DC leads are attached
  - If necessary
    - » Wiring between terminal block and magnet
    - » Strain relief for cables
    - » Safety covers
    - » Polarity labels and testing

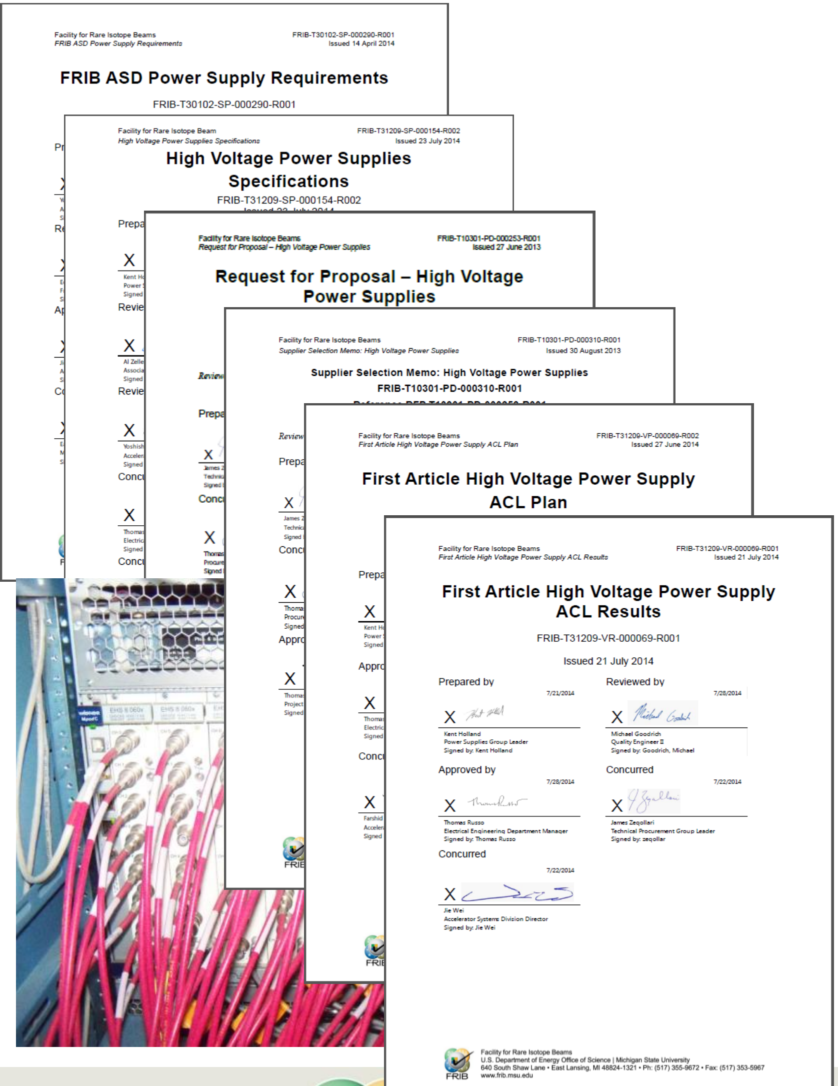


Superconducting Magnet (SCM) PS Procurement Strategy Defined



- Sigma Phi Electronics (previously Bruker)
  - Four in use at NSCL with zero failures since 2007
  - A respected company with many PS in service
    - » Provided a detailed proposal
    - » Low technical risk
  - Make vs. Buy decision → Buy
  - Sealed competitive bid
  - First Article phase out of three phase contract let
  - Supplier visit held 28-30 April 2014 for Factory Acceptance Testing
  - Supplier tested on SC magnet successfully
  - First Article SCM PS delivered in July, 2014
    - » FRIB Acceptance Testing is underway

High Voltage (HV) PS Procurement Strategy Defined


Facility for Rare Isotope Beams
First Article High Voltage Power Supply ACL Results
FRIB-T31209-VR-000069-R001
Issued 21 July 2014

First Article High Voltage Power Supply ACL Results

FRIB-T31209-VR-000069-R001

Issued 21 July 2014

Prepared by 7/21/2014
X
Kent Holland
Power Supplies Group Leader
Signed by: Kent Holland

Reviewed by 7/28/2014
X
Michael Goodrich
Quality Engineer II
Signed by: Goodrich, Michael

Approved by 7/28/2014
X
Thomas Russo
Electrical Engineering Department Manager
Signed by: Thomas Russo

Concurred 7/22/2014
X
James Zeqollari
Technical Procurement Group Leader
Signed by: zeqollar

Concurred 7/22/2014
X
Jie Wei
Accelerator Systems Division Director
Signed by: Jie Wei

- WIENER Plein & Baus GmbH / iseg
  - WIENER MPOD Control Crate and iseg 2-quadrant HV power supply modules for electrostatic quads and dipoles
    - » Higher efficiency and wider operating range than a 1-quadrant PS with output resistor
  - Standalone iseg HV PS for ion source
  - 382 iseg PS and 7 MPODs in use at NSCL, installed 2009-2012, with only one failure (Wiener crate controller)
  - Over 1M HV PS in service around the world
    - » 100k HV PS recently completed for project in Japan
    - » Low technical risk
  - Sealed competitive bid
  - First article phase out of 2 phase contract let
  - First article HV PS received, and failed acceptance testing due to minor hardware issue
  - Supplier visit held 5-6 May 2014 for revision 1 Factory Acceptance Testing
  - Rev 1 passed FRIB Acceptance Testing

iseg

WIENER Plein & Baus Elektronik

Room Temperature Magnet (RTM) PS Procurement Strategy Defined

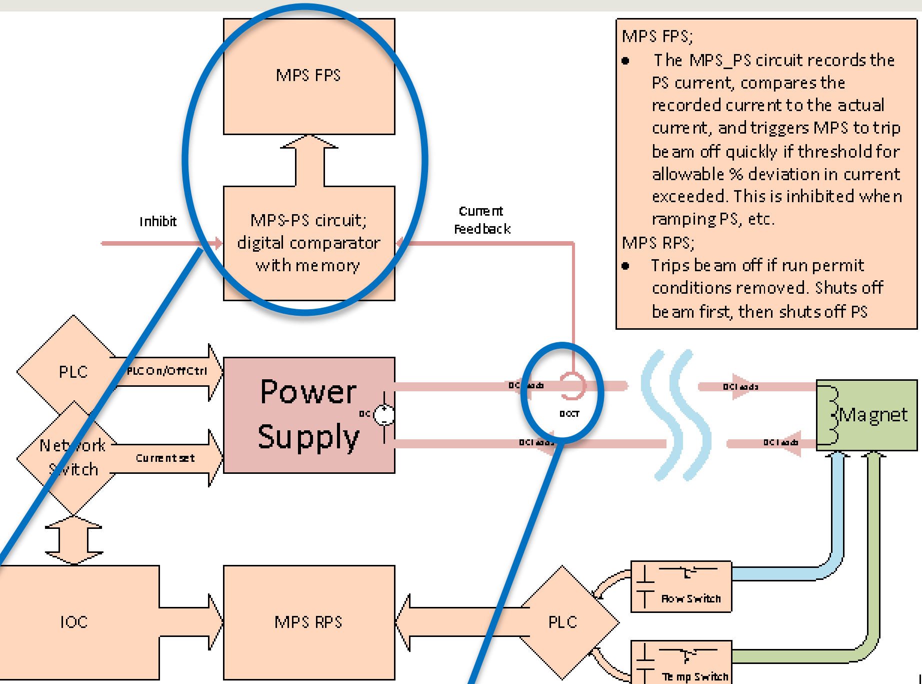
- Responses received from initial RFP
  - Multiple qualified sources identified
  - Low technical risk
    - » RT power supplies are COTS catalog items
    - » Loaner PS are available from top suppliers if necessary
    - » NSCL has many similar PS in service
      - No first articles are needed
- Final Specifications and RFP waiting for;
  - Clarification on change in requirements
    - » Series Dipoles
      - Separate RFP will be done for RT Dipole PS
        - » To ensure best value for the project
    - » Minor changes as combined function magnets are now separate function
  - Final magnet RFP – fall, 2014
    - » Decision for build-to-spec or build-to-print
      - Could cause minor changes in PS requirements
- Source selection on track for early 2015

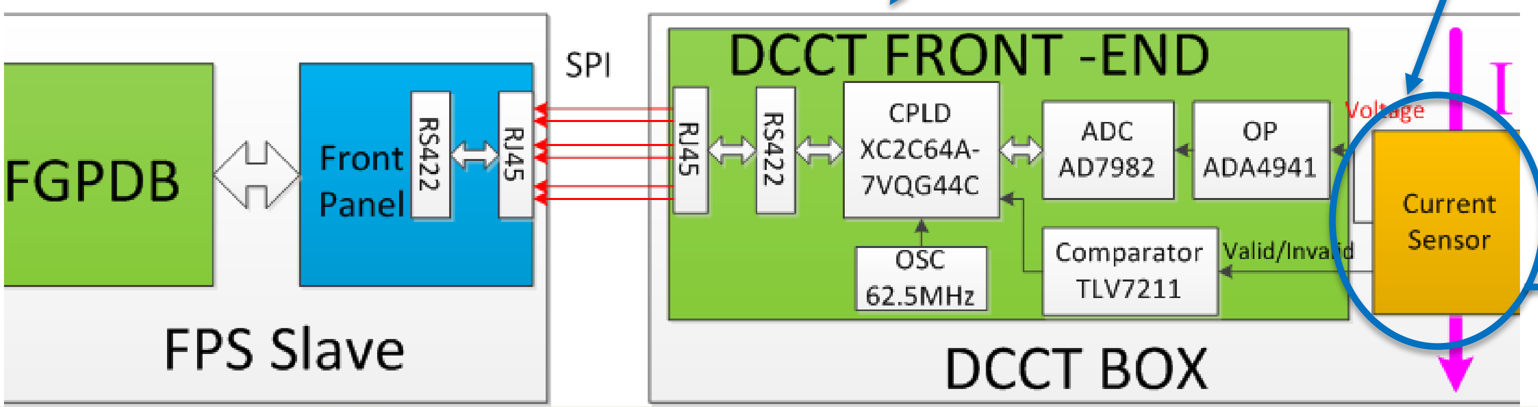
Concluding Remarks

- NSCL power supply operations, maintenance, and status.
- FRIB power supply requirements.
- FRIB power supply strategies.
- Questions or Comments?

Machine Protection System (MPS) / Dipole PS Circuit Interface Defined and Tested

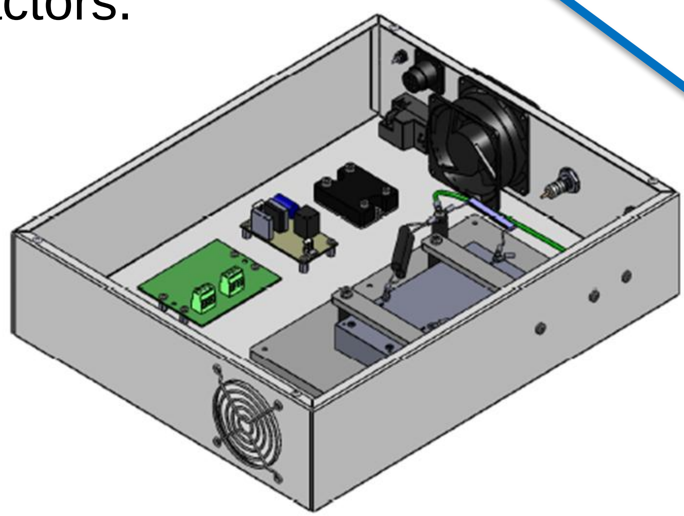
- A fast circuit is needed to monitor dipole magnet current
  - To protect the machine from damage due to drifting PS
  - If the current changes beyond a threshold, a fast protection circuit will shut off the beam in 35µs to prevent damage
  - Fail-safe interface between PS DCCT and Fast Protection System (FPS)
  - Digital interface between PS DCCT Box and FPS
  - FPS makes comparison digitally
- Non-critical PS will trigger the slower Run Permit System (RPS) by comparison in the Input / Output Controller (IOC)

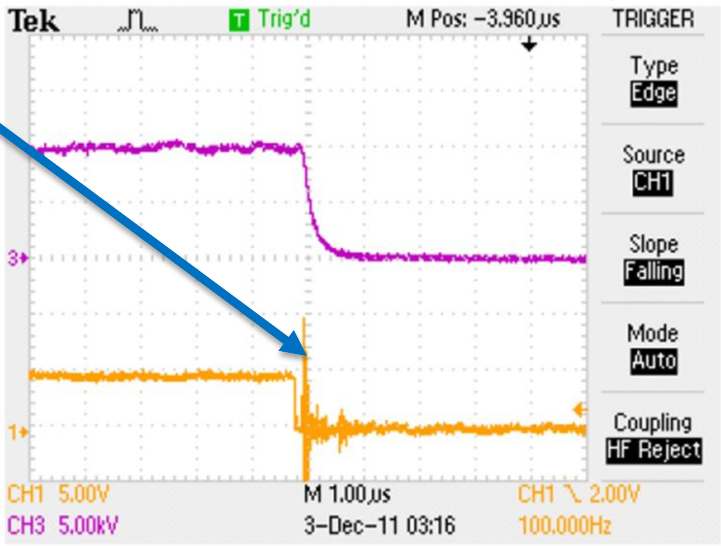




Electrostatic Dipole HV PS MPS/PPS Interface Defined

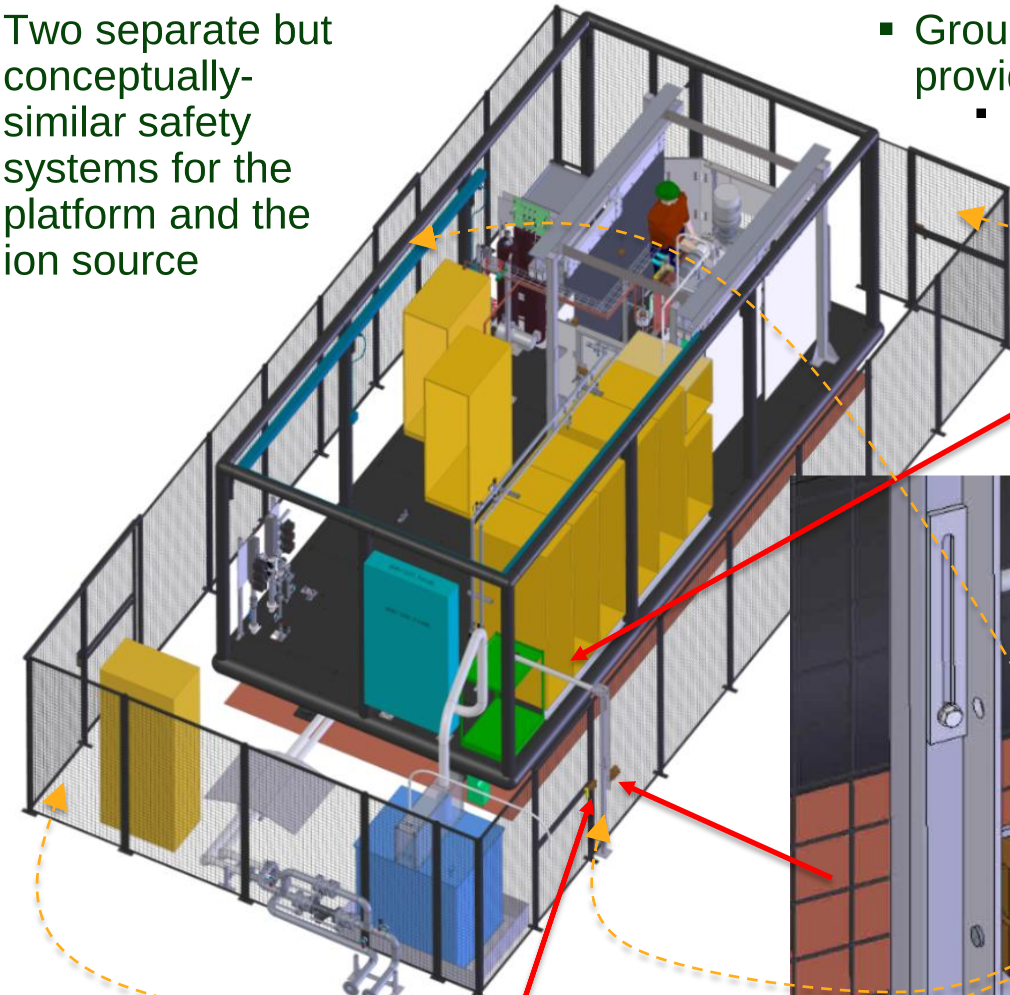
- MPS fast solid state abort switch
  - To protect the machine from beam damage, the voltage has to be turned off in ~1uS
    - » Noise on TTL signal will be mitigated by compartmentalizing components in RF enclosures
  - The chopper is a redundant method to abort beam in the required time
- PPS Mechanical shorting switch and AC contactors
  - Ensures no beam in tunnel
  - PPS will also control the high voltage of the Ion Source through redundant contactors.





Ion Source HV Safety Systems Integration
Kirk Interlocks Control Access to Platform

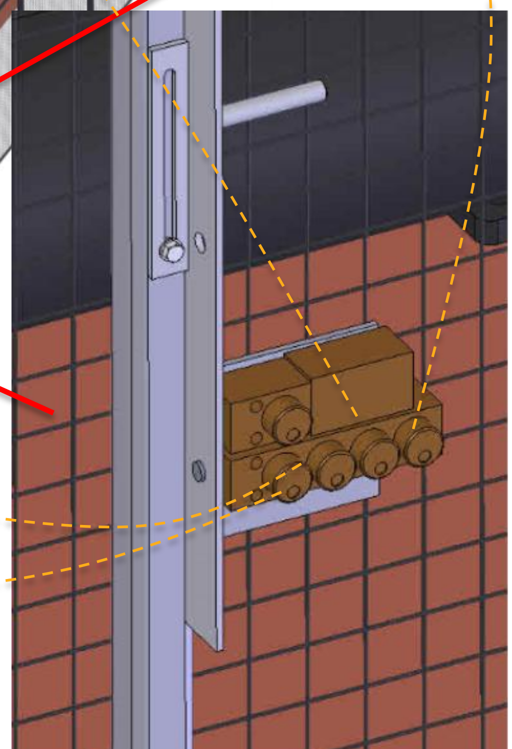
- Two separate but conceptually-similar safety systems for the platform and the ion source



- Grounding rods/hooks provided on each entry door
  - Auxiliary safety features
    - Ross relay
    - Light and sound alarms
    - Door switches
    - Crash button
    - Crane interlock

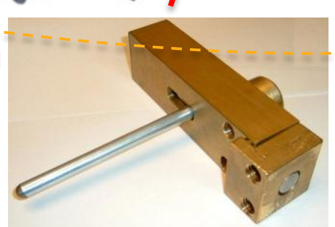
Grounding bar assembly closed

Turn PS off, power breaker off, interlocked, key released



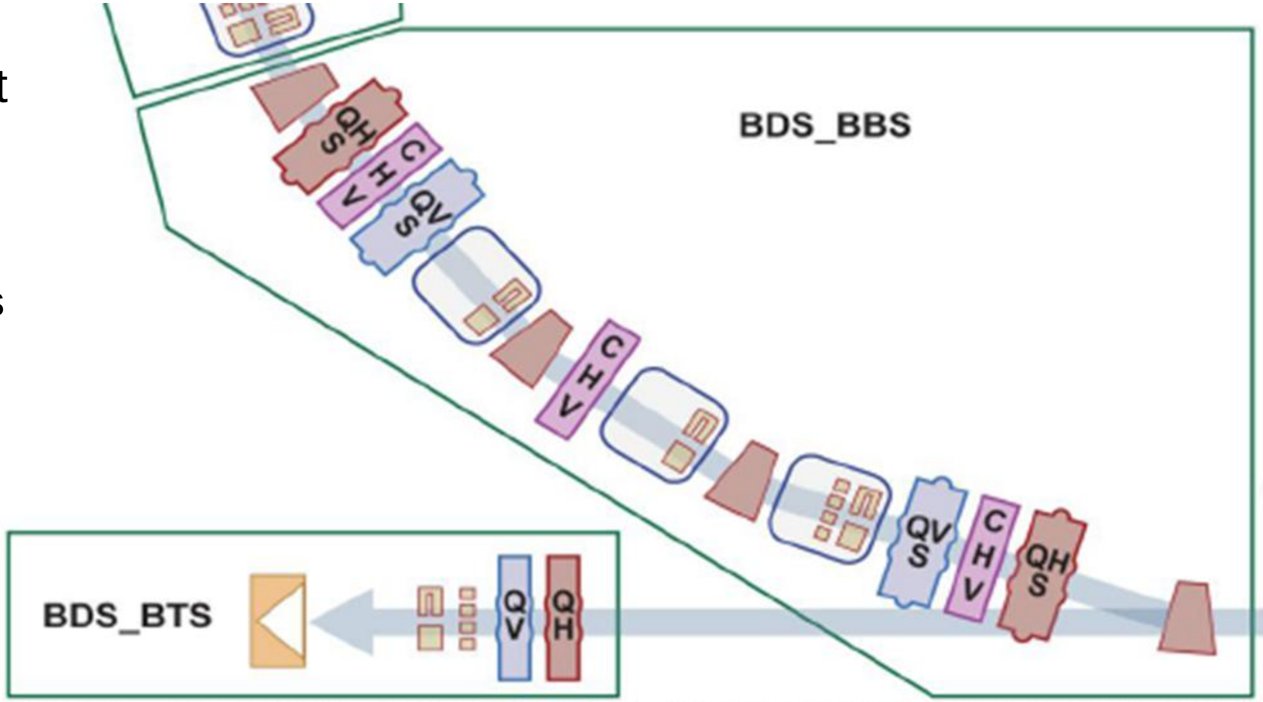
1. Upper bolt withdrawn, breaker key trapped
2. Grounding bar down, lower hole aligned
3. Lower bolt can be extended, door keys released
4. Door keys captured in door interlocks

Door interlocks with emergency release from inside



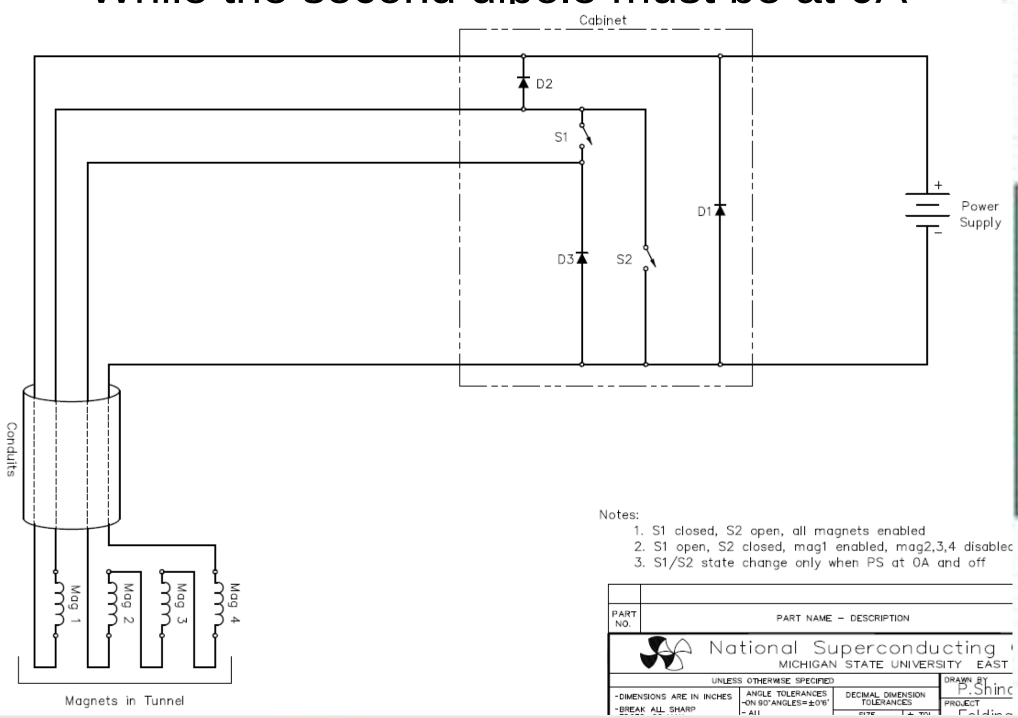
BDS Dipole PPS Interface Defined

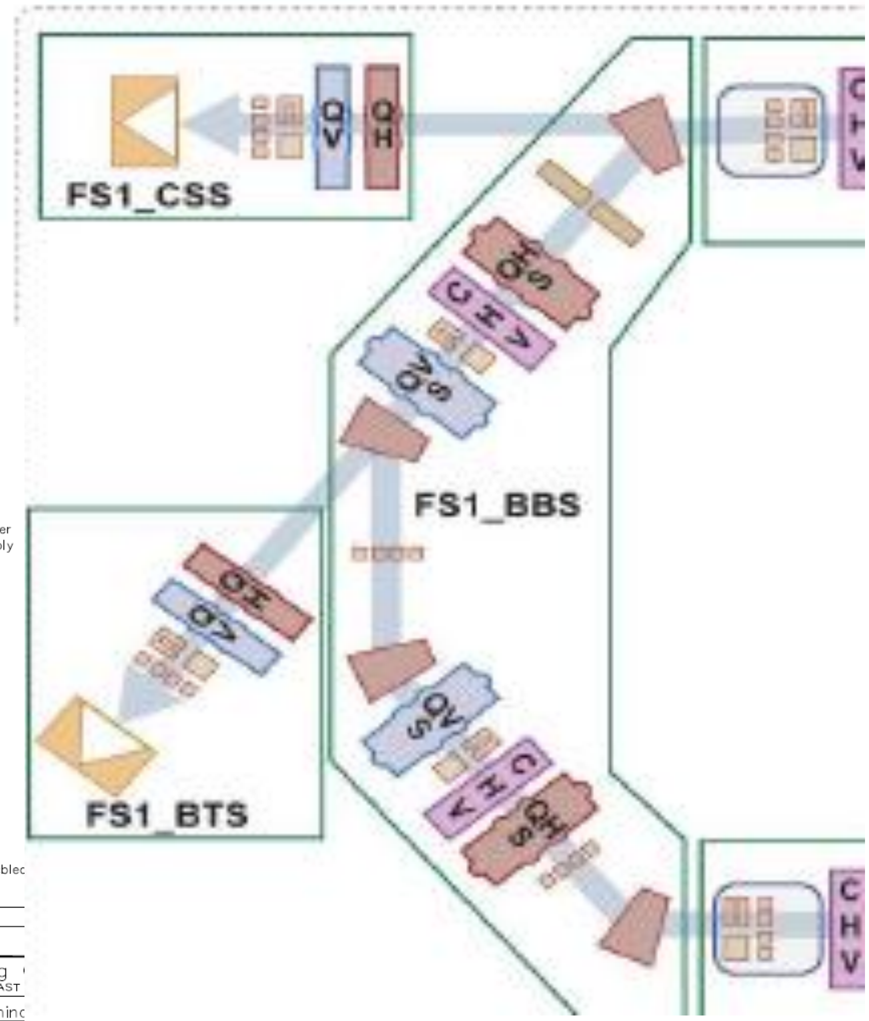
- To prevent beam from entering the target area, the bending dipole PS in the BDS will be monitored and controlled redundantly by the PPS
  - To ensure no AC power to the PS is present unless the target area is swept and secure
    - » Four bending dipoles in BDS area to bend the beam from LINAC to target
      - All four dipoles are powered by one power supply
    - » The power supply is equipped with redundant contactors
    - » When target area is occupied
      - PPS opens the contactors
      - Verifies contactor function via auxiliary contacts
    - » Additionally there will be a beam plug to ensure no beam is possible to target area



Magnet Interface Example FS1 Series RT Dipoles

- A disconnect switch is needed in FS1
  - When the FS1_BTS beam dump line is operating
    - » The first dipole must be on
    - » While the second dipole must be at 0A

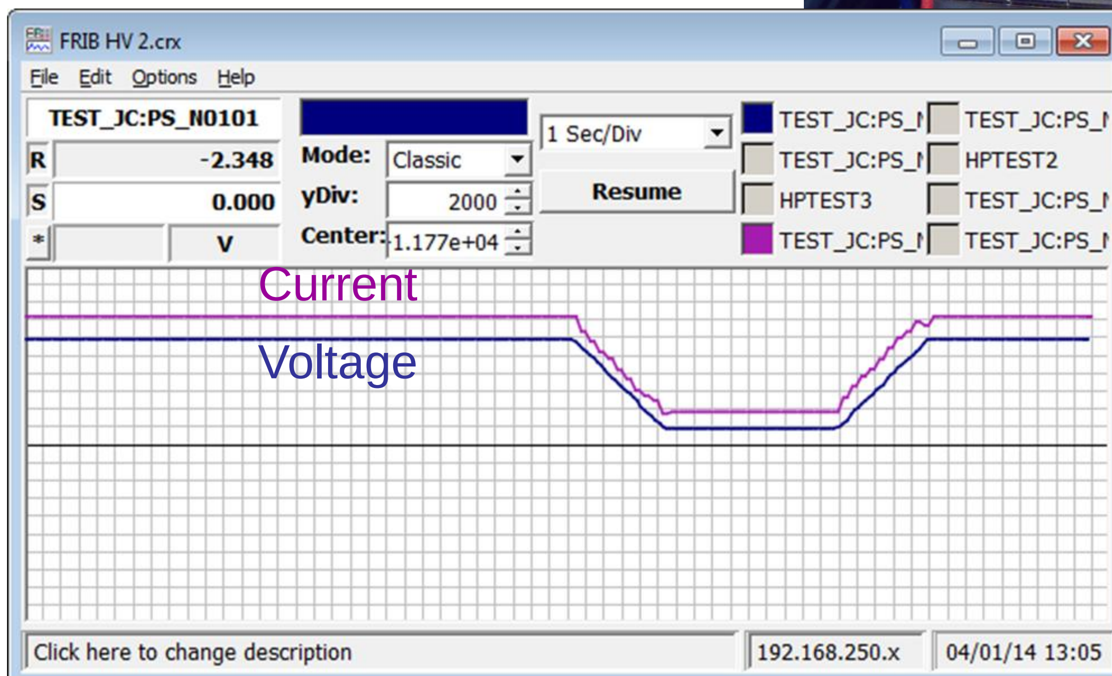




HV PS First Article Status

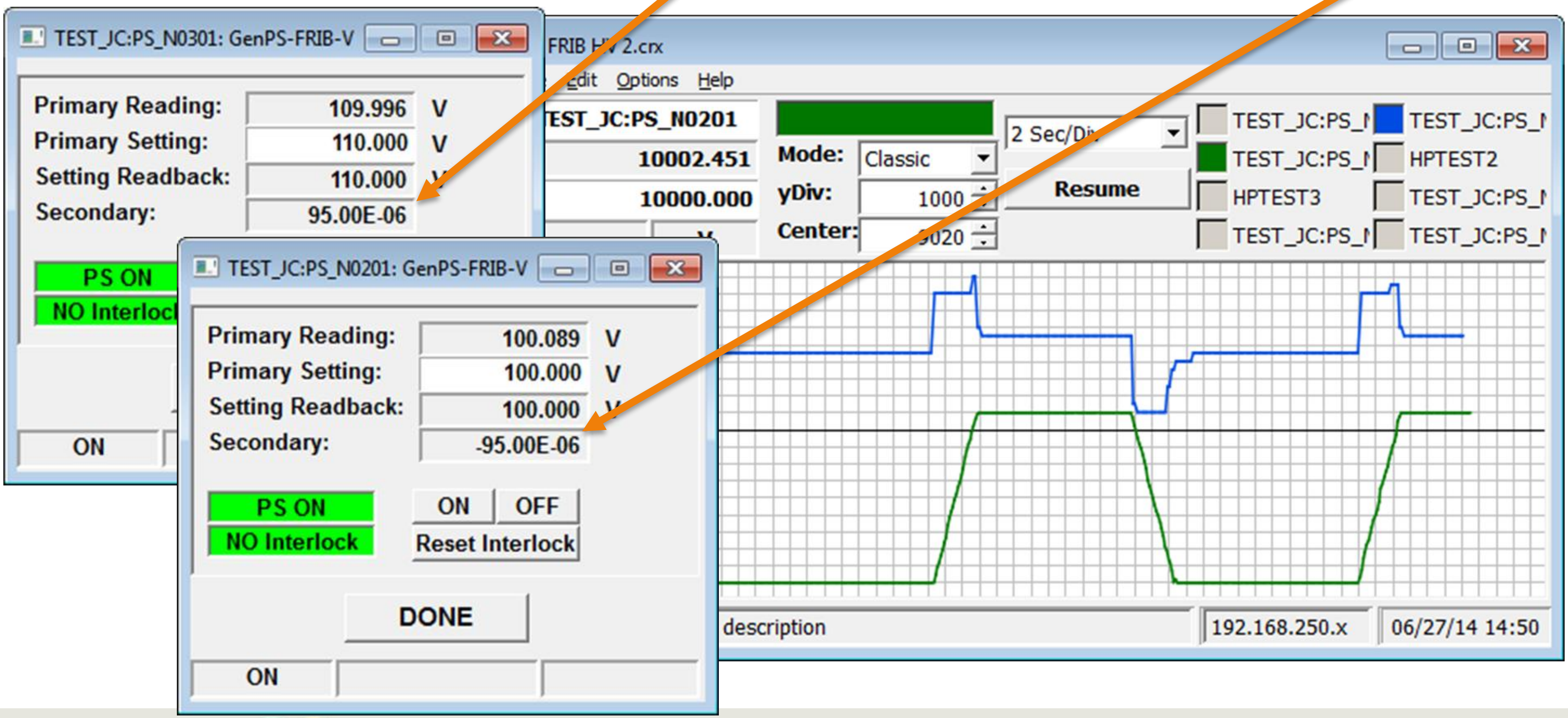
- HV PS First Article status
  - Supplier visit held 5-6 May 2014 for revision 1 Factory Acceptance Testing
  - Rev 1 passed FRIB Acceptance Testing
  - Requirements revised – no changes for HVPS
  - Specs finalized – no changes

- Rev 0 first article HV PS was received in February 2014
  - Testing revealed a hardware issue with the current read-back
    - » With capacitive load, voltage waveform shows textbook 2-quadrant operation, however the current measurement did not (I=C*dV/dt)
  - Revision 1 first article HV PS
    - » Supplier redesigned the current measurement circuit
    - » Revision 1 passed FRIB Acceptance Testing, the current readback issue was resolved



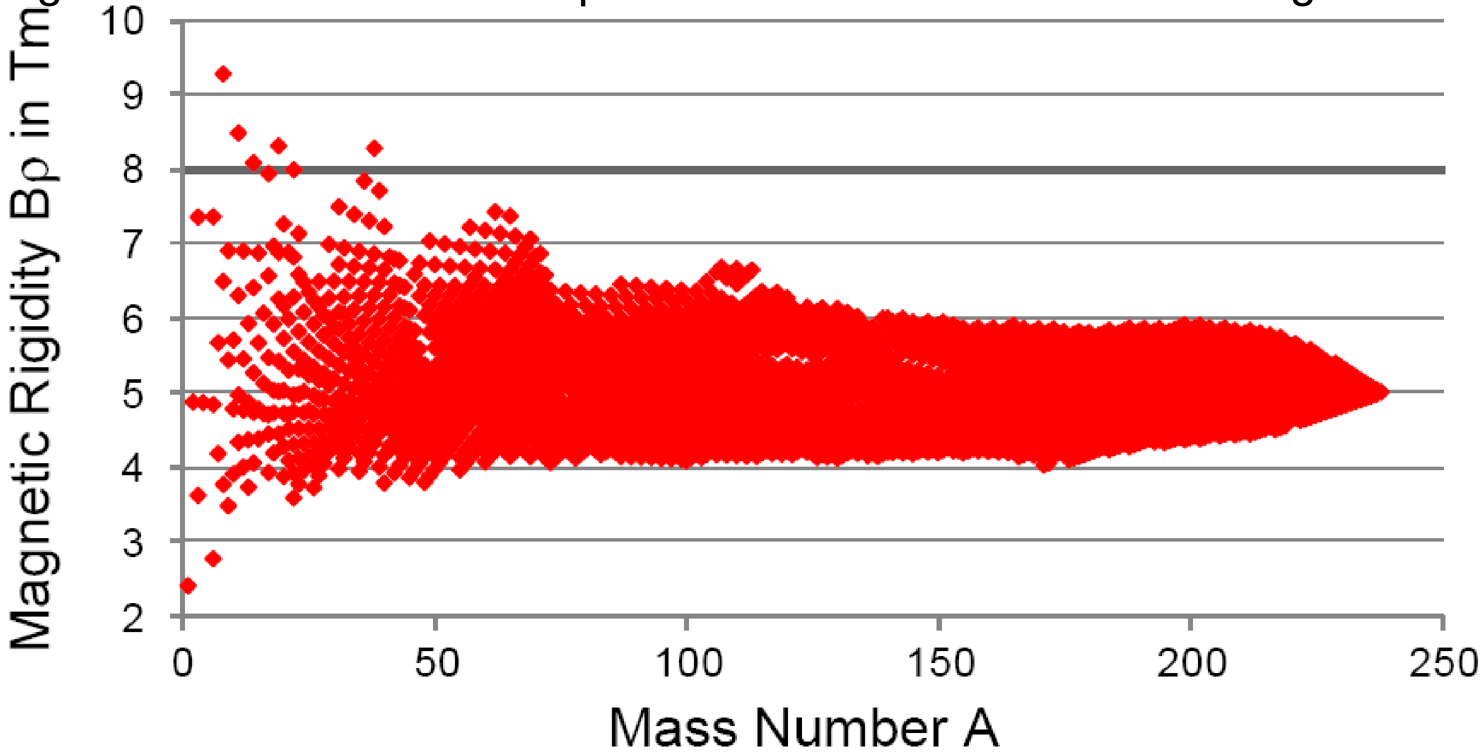
Rev 1 HVPS Two Quadrant Current Read-Back Issue Resolved

- Test 1, ramp voltage into capacitive load
- Test 2, Use existing HVPS to source, and force FRIB HVPS to sink thru 100kΩ



ESD SCM PS Margin Documented

- PS requirements based on 8 Tm
- Sufficient margin exists as most beams are at magnetic rigidities below 7 Tm
  - There are alternatives for beams with rigidities higher than 7 Tm by reducing the primary beam energy, or thicker targets could be used, or a combination of the two resulting in similar rates. Either option will result in lower PS settings



SCM PS Detailed Design [1] Component Margin Reviewed

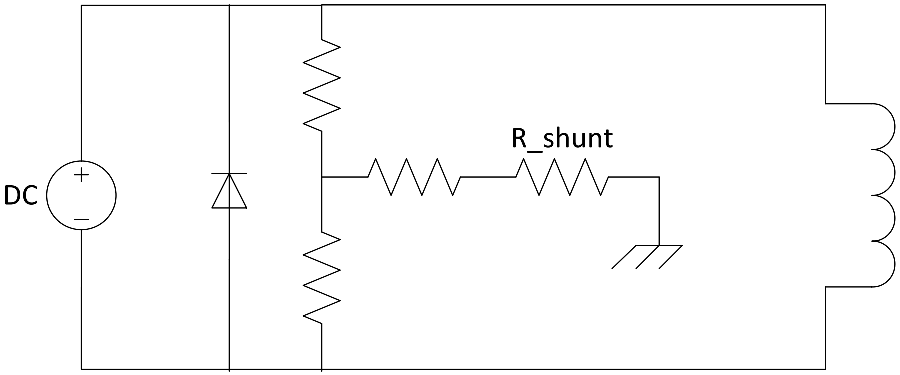
- DC link AC/DC max power calculated = 1.1kW
  - AC/DC PS = 2 // 24V 27A = 24V 54A = 1.3kW, 18% margin
    - » Note that DC link power drops while regulating,18% is only while ramping
  - AC/DC input max = 1.42kVA
    - » 2 // 24V 27A PS, input 7.1A @ 100V, =~ 14.2A (~12.9A at 110V)
    - » 14.2A is at 1.3kW, while max DC link power is 1.1kW
    - » ~10.9A at 110V and max 1.1kW DC link
      - Again note that the DC link input current drops while regulating
  - Line filter – 16A
    - » 13% margin using the worst case 14.2A
    - » 46% at 10.9A
  - Contactor
    - » Rated for 20A
    - » 40% margin using the worst case 14.2A
    - » 80% at 10.9A
    - » 10M cycles
- IGBT
  - Tj calculated 75C, rated 150C
  - >>20k thermal cycles, ~54 years, non-issue
  - Rated 300A @ 80C operating Tc case temperature.
  - Tc is ~ 40C heat sink temp
  - Limited to 70C by the thermal switch.
  - Case is rated for 100C max
- D1 and Chopper elements
  - Contacted Supplier for more info
  - No thermal issues during FAT
- DC filter inductor – 125A, 15A @ 20kHz
  - ~45C measured
- DC filter caps
  - rated 200V, dump voltage 80V
  - rated at magnet current
  - 11k hrs. @ 85C, Sigma Phi claims 8X expected lifetime at 55C, 88k hrs. = ten years
  - Ambient air inside chassis measured ~40C

SCM PS Detailed Design [2]
Component Margin Reviewed

- Dump Resistor
  - 20% margin added to stored energy
  - Simulations showed the housing temp = 115C (peak housing temp is ~3min after t0), and wire = 750C
    - » 'Compact Brake Resistor' rated for 1200C
    - » Datasheet states 'if temperature rise is less than 900-1000K the resistor should work for your application'…'However it is recommended to verify the results of the simulation'
    - » The simulation was verified as part of the FAT
      - 3 min after t0, the housing temp = 72C which is better than the simulation
- DCCT - 200A
- Cables
  - AC = 14AWG,
    - » rated 32A for chassis wiring
    - » worst case 14.2A
    - » ~10.9A at 110V and max 1.1kW DC link
  - DC link 1 = 12AWG
    - » rated 41A for chassis wiring
    - » worst case 27A
    - » ~23A (from Sigma Phi calculation)
  - DC link 2 = 8AWG
    - » rated 73A for chassis wiring
    - » worst case 54A
    - » ~46A (from Sigma Phi calculation)
  - DC Out = 2AWG
    - » rated 181A for chassis wiring
    - » worst case 107.5A
- Summary of component review
  - The 100A power supply is built to run at 6V / 100A continuously
  - Running at 2V / 95A continuously for operations is not desired, but acceptable
    - » Fallback position is to run solenoids at lower fields (95A is for 8T, 7T is acceptable)

Grounding Plan
HV and SC PS Complete. RT PS Under Consideration

- The PS chassis (equipment ground) must be firmly tied to the facility ground mesh (FGM)
- The DC output grounding;
  - HV cables are coaxial with a ground braid firmly tied to the FGM
  - SCM PS ≥100A will have an internal hard ground with ground fault detection
  - RTM PS grounding under consideration, PS above a certain current will be either be;
    - » Soft grounded, with a high resistance to both output terminals, a conceptual design is shown in the figure 4. The existing protection diode box would be modified to incorporate soft ground resistors with provisions for future ground fault monitoring by either;
      - Shunt resistor, with analog input to PLC
      - Optocoupler, with digital input to PLC
    - » Hard grounded thru an indicating fuse, with digital input to PLC. Could be incorporated in diode box
    - » PLC inputs may be future upgrade
      - Baseline is preventive maintenance task
        - » Check for ground faults annually
    - » Modify existing NSCL diode box
      - Diode selection is underway



DC Cable Conduit Heat Mock Up Test and Simulations – Ensures Properly Rated Cables

- Mutual heating between conduits has been verified
  - A mock up test has been completed
  - Simulation model has been verified by comparing results from the mock up →
  - The verified model is fed into a worst-case multi-conduit chase model ↓
  - Results show that only a few of the largest cables, in highly congested areas, needed to be spread out or use larger cables
  - Details in talk 09 'Conduit Heat Testing and DC Cable Allocation'